Ultra-Cold Neutron Physics at LANSCE

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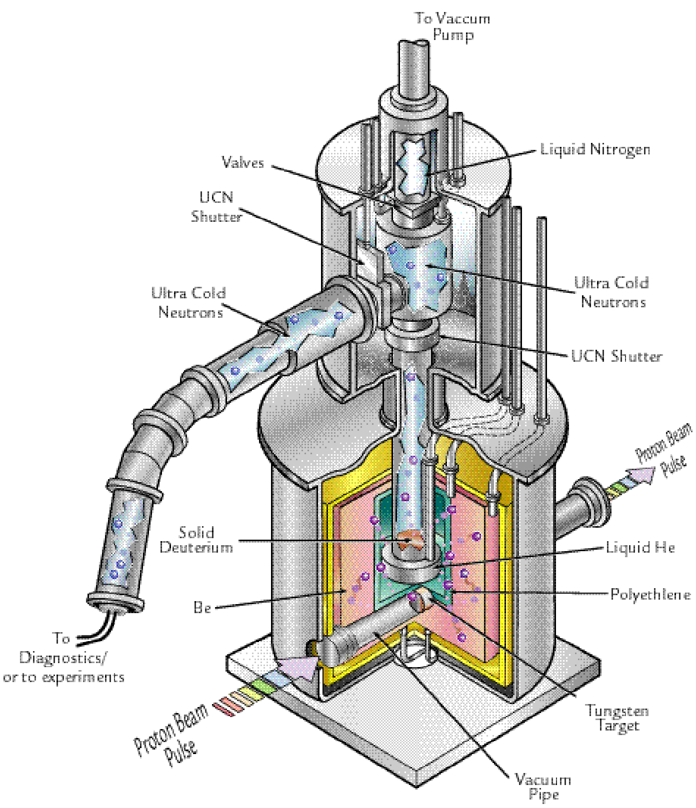
An international collaboration working at LANSCE has recently demonstrated that they can construct what will be the most intense ultra-cold neutron (UCN) source in the world—a source that ultimately will be competitive with other approaches in searching for new physics. This source works by moderating neutrons from a spallation target into the UCN regime using solid deuterium at 5 K. Our initial physics research will center on a measurement of the asymmetry in the direction that electrons are emitted with respect to the neutron spin in the beta decay of polarized UCNs. Because of the unique properties of UCNs, we expect to greatly reduce all of the major systematic problems that have plagued reactor measurements of the beta asymmetry. We expect to determine the weak vector coupling constant (a fundamental constant of nature) with unprecedented accuracy. Comparing our measurement with that predicted by the standard electroweak model, which unifies the electromagnetic and weak interactions within the nucleus of an atom, we can carry out a sensitive search for possible new physics predicted by unified field theories, such as the existence of new particles that mediate the weak interaction. In addition, with the significant increase in UCN intensity that can be produced at LANSCE, we will be able to investigate possible new applications of UCNs in materials science and biology.

The Advantages of Ultra-Cold Neutrons

Ultra-cold neutrons (UCNs) are neutrons whose wavelengths are sufficiently long enough (typically greater than 500 Å, which corresponds to an 8-m/s neutron velocity) to allow them to undergo total external reflection at all angles from the surfaces of a variety of materials. This feature allows for the manufacture of bottles that can physically store UCNs for periods of 100 s or more. Thus, we can then prepare a compact source of stored neutrons for use in measurements of fundamental physics.

There are two significant advantages that UCNs offer compared to experiments done using cold neutron beams from reactors: polarization and background. We can produce 100% polarization of UCNs by passing them through a strong magnetic field gradient. In practice, passage through a field of 7 T is sufficient enough to polarize 100% of the UCNs because the kinetic energy of a UCN is so small that a UCN of one spin state cannot overcome the potential barrier caused by the interaction of the neutron's magnetic moment with the external magnetic field. In contrast, very detailed measurements needed to be made on reactor beams to determine the value of the polarization of the neutrons. Secondly, a guide tube oriented in a nondirect path between the UCN source and the experimental area effectively reduces background. Other particles also created at the UCN source travel through the guide tube, striking the sides where they are stopped. UCNs, however, simply move around bends in the guide tube effortlessly, bouncing off the sides and on to the detectors located a large distance from the UCN source. Also, because UCNs can be produced and stored at a spallation source, data can be taken without the continual presence of beam on the UCN source. Sensitive beta-decay experiments can be performed with much smaller backgrounds than those produced at a reactor.

We formed a collaboration in 1994 with Professor Serebrov's group at the Gatchina reactor in Russia to develop solid deuterium (SD_2) as a potential UCN source. This work indicated the potential to achieve a significant increase in UCN production compared to existing methods. In the spring of 1998, our group developed a design for a compact SD_2 UCN source. We constructed a prototype SD_2 source with which we have carried out a series of measurements in the Blue Room at the WNR (Fig. 1). The 800-MeV proton beam from the LANSCE accelerator strikes the tungsten target, producing about eighteen neutrons for every incident proton. These neutrons have a typical energy of a few MeV and are reduced to cold neutron temperatures (about 40 K) by scattering in polyethylene moderators at 4 K and 77 K. The moderators are housed within a cold (77 K) reflector assembly composed of blocks of beryllium. The cold neutrons are down-scattered into the UCN regime as they interact with the SD_2 and are then confined within the ^{58}Ni-coated guide tube that contains the SD_2. The UCNs then leave the SD_2 and are transported along the guide to a proportional counter filled with a small amount of ^{3}He where they are detected. We chose the geometry shown in Fig. 1 because essentially only UCNs can be transported around the bends in the guides. UCNs must also fall at least 1 m down the guide so that they acquire enough kinetic energy by gravitational acceleration that they can pass through the thin, aluminum entrance window of the detector.



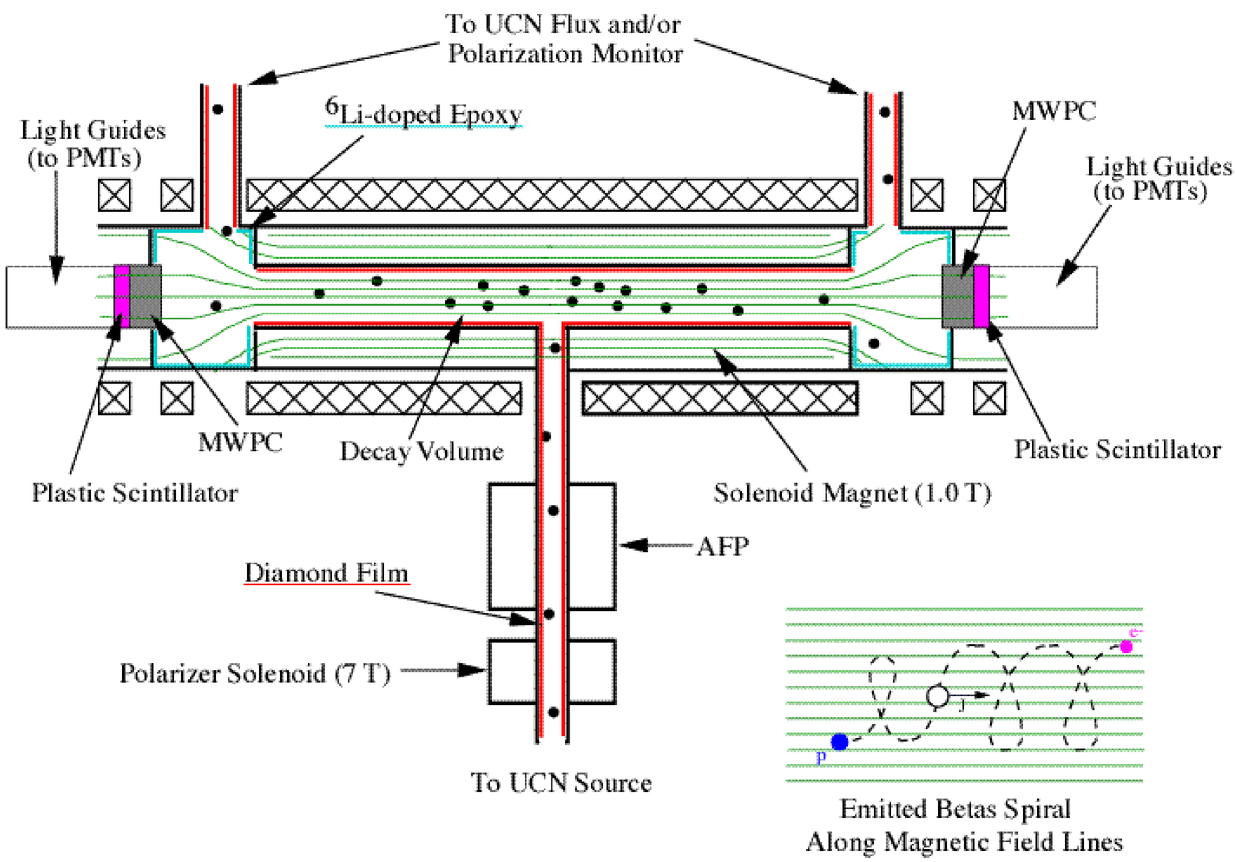
▲ **Fig. 1.** *Concept drawing of the prototype UCN SD_2 source. The 800-MeV proton beam from the LANSCE accelerator strikes the tungsten target, producing about eighteen neutrons for every incident proton. These neutrons are reduced to cold neutron temperatures (about 40 K) by scattering in polyethylene moderators at 4 K and 77 K. They down-scatter into the UCN regime as they interact with the SD_2 and are then confined within the ^{58}Ni-coated guide tube that contains the SD_2. The UCNs then leave the SD_2 and are transported along the guide to a proportional counter filled with a small amount of ^{3}He where they are detected.*

We have already produced a significant flux of UCNs and measured both the production rate and the lifetime of UCNs in the SD_2. Our first observations indicated a much shorter lifetime (and therefore more absorption) in the source than we had calculated. Although we tried different means of freezing the deuterium and varied the SD_2 temperature and volume, we observed little change in the UCN rate. In the summer of 1999, we realized that the factor limiting the production rate was the fraction of "para" deuterium in which the spins of the two deuterium nuclei are lined up to form a total nuclear spin of 1. Deuterium also exists in the "ortho" state in which the spins of the two deuterium nuclei add up to form a total nuclear spin of 0. By converting the fraction of molecules from the para state into the ortho state (which is the ground state) using a cryogenic converter, we observed an increase in UCN rates. We recently carried out a series of measurements that has validated the physics model that we developed and demonstrated that we can construct a dedicated UCN source at LANSCE that will be the most intense in the world. In our most recent runs, we bottled UCNs with a measured density of 33 UCNs/cm^3 in a stainless-steel bottle. We accomplished this by using only eight low-intensity proton-beam pulses from the accelerator spread out over 3.5 s. This density can be compared with the world-record density of 41 UCNs/cm^3 measured at the Institute Laue-Langevin (ILL) research reactor in France. The efficiency of our method is particularly impressive. We produced a comparable UCN density as that produced at the ILL using only 300 W of beam power from the accelerator compared to the 59 MW of power at the ILL reactor! With an optimized source geometry and an average beam power of 3.2 kW, we are now quite confident that we can reach a density an order of magnitude higher than possible at the ILL reactor. This method could be easily scaled to even higher beam currents and thus higher UCN densities.

We are proposing to construct a dedicated SD_2 source in Area B at LANSCE (Fig. 1). The proton beam would strike the tungsten target for a fraction of a second, producing spallation neutrons that are first cooled down to 77 K and then cooled further into the UCN regime, as described above. The UCNs produced would move into a storage bottle located above the source. A valve between the source and bottle would close after one second. This procedure would be repeated every 10 s with a time-averaged beam current of only about 4 μA. As the LANSCE accelerator is capable of providing 1 mA of protons, this is a very modest beam current whose value is currently set by the fact that the facility is not authorized for Category-3 nuclear facilities. Even with the low beam current, we expect to produce a density of UCNs in the storage bottle of about 400 UCNs/cm^3, which is an order of magnitude better than what has been achieved anywhere else in the world. We plan to use this source to feed the beta-asymmetry experiment that is shown schematically in Fig. 2.

The UCNs from the source first pass through a strong (7 T) solenoid in which they are polarized. They then pass through an adiabatic-fast-passage (AFP) spin flipper in which the direction of the neutron spin can be reversed by exactly 180^o. The UCNs are then injected into the center of a 3-m-long UCN trap that is surrounded by a 1-T superconducting solenoid magnet. About 1% of the UCNs will beta decay before they exit the trap. The electrons produced from the neutron beta decay will spiral along the magnetic field lines to the ends of the solenoid. At the ends of the solenoid, the magnetic field is reduced to focus the electrons in the forward direction to dual detectors—a multiwire proportional counter (MWPC), which measures the position of the electrons, and a plastic scintillator, which measures the total electron energy. This dual detector system reduces backgrounds by an order of magnitude over previous reactor experiments that used only a scintillator. The experiment measures how many electrons are emitted in the same direction as that of the neutron spin compared to the number emitted in the opposite direction. The use of the AFP spin flipper allows us to effectively interchange the role of the two detectors at the end of the solenoid and is crucial in studying systematic effects in the beta-decay experiment resulting from the slightly different characteristics of the two detectors.

The beta asymmetry has been measured to be about 10% using cold neutron beams at reactors. We anticipate that in three months of running we can



▲**Fig. 2.** *Schematic view of the spectrometer to be used in the beta asymmetry measurement. The UCNs from the source are injected into the center of a 3-m-long UCN trap that is surrounded by a 1-T superconducting solenoid magnet. About 1% of the UCNs will beta decay before they exit the trap. The electrons produced from the neutron beta decay will spiral along the magnetic field lines to the ends of the solenoid. At the ends of the solenoid the magnetic field is reduced to focus the electrons in the forward direction to the MWPCs, which measure the position of the electrons, and the plastic scintillators, which measure the total electron energy, on either end of the spectrometer.*

reach an accuracy of 0.2% for the asymmetry compared to the 2.5% range in values from different reactor experiments. We will be able to not only resolve the discrepancy in the reactor experiments but also measure the weak vector coupling constant much more precisely and thus search for new physics (i.e., interactions mediated by new elementary particles) predicted to exist by theories that attempt to unify the known forces of nature into one "grand" theory. Ultimately, by measuring other angular correlations in neutron beta decay with UCNs and measuring the neutron lifetime, we should be able to probe for new physics with UCNs on a scale comparable to that of new high-energy accelerators (i.e., the Large Hadron Collider now under construction at CERN). Thus, the high UCN intensities that we expect to achieve with a new SD_2 source at LANSCE will offer a powerful new tool for fundamental physics that is competitive with other approaches around the world in searching for new physics.

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